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Study of a Continuous Drill and Blast Tunneling Concept

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STUDY OF A CONTINUOUS DRILL AND BLAST TUNNELING CONCEPT

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13. ABSTRACT

A spiral drilling pattern is described which offers high efficiency drill and blast tunneling via frequent small blasts rather than the occasional large blasts of conventional practice. Preliminary design work is presented for a combined drilling, loading, shooting, and mucking machine which would stay at the tunnel face, providing continuous drill and blast progress. Advance rates in excess of 13 feet per hour in an 8 x 8 foot horseshoe tunnel are predicted using off-the-shelf (except for automated explosive loading and initiation) components.

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1. Program Summary

The program reported herein is a study of an unusual spiral tunnel face geometry, conceived to permit continuous drill and blast tunneling progress.

The program consisted of a feasibility study of the spiral blast pattern itself, together with a very preliminary design effort to establish concepts and characteristics of a machine to remain at the face, performing drilling, loading, shooting, mucking, and ventilation tasks in an essentially continuous process.

A literature search and consultations with qualified blasting experts were employed to establish the feasibility of the pattern per se. It was quickly established that the spiral blast pattern was not only quite reasonable - it was actually in use. More detailed studies were then made to define a specific geometry to be used as the basis for the machine design effort.

An 8 x 8 foot horseshoe tunnel section was selected as reasonable in size for possible prototype development, and because it embodies all geometric conditions that would be encountered in round, square and rectangular headings, as well as horseshoe. A crawler mounted vehicle was conceived to fit within this horseshoe section, carrying all drilling, loading, explosive initiation, mucking and ventillation equipment. Except for automated loading and initiation equipment, conventional, commercially available components may be used throughout. Even with today's conventional components, very attractive tunneling rates are possible by the simple expedient of permitting these components to operate continuously.

It will obviously be necessary to automate the loading and initiation of blasting agents in any continuous drill and blast tunneling machine. This important aspect of the development has been studied by the Bureau of Mines in a separate program (1).* Several blasting agent candidates have been identified along with a suitable initiation scheme. Inputs from that program have been available as necessary for the present program, and loading and iniation requirements are believed to be compatible with all other design requirements. Adequate space for loading and initiation equipment is available, although details of such equipment are not available at this time.

To illustrate the unusual geometry of the spiral blast pattern and the major components of the continuous blast machine, a simple model has been constructed.

Background material is contained in Section 2. The spiral blast concept is described in general in Section 3, which also contains a brief history of its origin and use, and a general statement of the concept's advantages over both conventional drill and blast practice and today's boring machines. Section 4 describes and illustrates the selected horseshoe geometry in detail. Section 5 describes results of the machine effort while Section 6 gives performance projections for the machine. Section 7 contains conclusions and recommendations.

*Numbers in parenthesis indicate references at the end of the report.

2. Background

The need for substantial advances in underground excavation technology has been recognized and is well documented. In response to this need, a number of research and development programs has been undertaken, many funded by the ARPA Program for Rock Mechanics and Rapid Excavation, as was the work reported herein. This work is a study of a concept to apply the economies of drill and blast rock fragmentation in a virtually continuous tunneling process.

The "conventional" drill and blast technique is the most economical method for the bulk removal of rock material. This is particularly true in hard rock, but it is also true in soft rock so long as bulk removal is the intent, as in many mining systems or in producing large underground chambers. However, in the advancement of a relatively narrow heading, as in tunnel driving, the cyclic drill, load, shoot and muck process inherent to the conventional drill and blast system is inconvenient, slow and costly. The disadvantages of such cyclic operation have long been recognized as have the corresponding advantages of a continuous drill and blast system. Therefore, no general comparison of the two is necessary herein, but, rather, specific comparisons will be made as appropriate for the spiral blast configuration under study.

Note that even under the disadvantages of conventional cyclic advance, drill and blast techniques are still more economical than boring methods under many conditions. Thus, if a continuous drill and blast technique could be developed it would appear to offer substantial savings over both the conventional drill and blast method and, under many conditions, present continuous tunneling boring practice as well. That is, if the cyclic problems can be avoided in narrow headings, then the recognized bulk excavation economies of drill and blast can be enjoyed in a wide range of rock types, not just in hard rock.

In addition to the economic penalties associated with cyclic advance, the conventional drill and blast system can, under some conditions, suffer additional problems which would be overcome by the present system. The drill and blast cycle is usually carried out with the greatest advance per round possible. This is normally limited by the depth of the cut than can be produced to open room for efficient blasting of subsequent segments of the round. With long rounds, blasts are quite heavy with two possible detrimental effects: damage to surrounding structures caused by shock and vibration; and excessive damage to surrounding rock. Indeed, a large fraction of temporary roof support is believed to be necessitated by this excessive rock damage.

Also, pulling long rounds naturally exposes a correspondingly long portion of unsupported roof after each round. If unsound rock conditions prevail this can be dangerous or impossible. It is then necessary to shorten the length of the round to produce an unsupported new roof of shorter span which will be self-supporting while temporary roof supports are installed. Unlike present continuous boring techniques, conventional drill and blast techniques do at least possess sufficient flexibility to continue progress under such difficult conditions, but producing short rounds with equipment sized for longer rounds is done at a lower advance rate and higher cost.

This report describes a study of a new blasting pattern which, in simplest terms, replaces the occasional heavy blast of conventional practice with frequent, much smaller blasts. The objective, of course, is to reduce the size of individual blasts to a level which can be withstood by a properly shielded machine adjacent to the face. This machine, which would perform drilling loading and mucking functions, would not be withdrawn for blasting, and a virtually continuous process could be carried out. It is also necessary in any continuous process to provide ventilation sufficient to handle the blasting fumes as generated. This is also made possible by minimizing the size of individual blasts.

One cannot simply reduce the size of individual blasts while maintaining a high blasting efficiency (and economy.) The overal pattern must be designed to provide a favorable geometry for each individual shot. The present pattern is an unique spiral arrangement that places a plane free face adjacent to every shot, thus providing one of the most efficient geometries for every individual shot.

The economy enjoyed by the drill and blast method (to which more exotice excavation means are often compared with discouraging results) stems from two factors: explosive energy is relatively cheap, and this energy is released so as to cause rock fragmentation largely through tensile failures. The relative ease and efficiency of tensile rock failures have long been recognized and studies have been undertaken to better understand this behavior (2,3).

The spiral blast pattern described herein is exptected to provide very high blasting efficiency by exploiting tensile waves reflected from a free surface adjacent to each blast. In general it would seem that, at least for the present, one cannot neglect the drill aspect of the drill and blast method - the explosive must be placed beneath the rock surface to most effectively utilize its energy.

Other work (4) has been directed to the utilization of explosive energy released at the surface to avoid the necessity for drilling blast holes. While no doubt less efficient, the simplicity of this approach and the ease with which a virtually continuous process can be produced may offset its relatively high explosives consumption. On the other hand, the spiral blast pattern offers the efficiency of the conventional drill and blast process without the cyclic disadvantages heretofore "inherent" to that process, and, possibly, with economy superior to either that process or today's continuous systems. It is also possible that a combination of the spiral blast pattern with the surface explosive method may ultimately prove advantageous.

3. The Spiral Drill and Blast Concept

This section will describe the spiral drill and blast concept in general terms, while Section 4 contains specific geometry suggested for early field testing.

3.1 The Problem

The basic problem is to devise a system which can apply the known economies of the drill and blast excavation system in a continuous or virtually continuous manner. In simple terms, then, if the process is to be continuous all aspects of the process, including drilling, mucking, ventilation, and roof support (if necessary) must also be continuous. It seems obvious that the blasting process itself, if not truly continuous, must consist of frequent small blasts so as to permit virtually continuous progress, muck flow, ventilation requirements and so on. Similarly, it is obvious that the entire process must be carried out by a single machine, suitably shielded so that it need not be retracted from the face during blasting.

Clearly, if the individual blasts are small enough, all of the machine design aspects of the problem can be handled, including continuous mucking, shielding, and continuous ventilation. The problem then reduces to the specification of a blasting pattern than can efficiently excavate with a series of relatively small blasts.

3.2 The Solution, the Spiral Blast Pattern

The spiral blast pattern seeks to promote efficient blasting by providing a plane free surface adjacent to all material that is to be removed. Thus each individual bore hole, loaded to relatively low explosive density, provides efficient performance by blasting to a free face.

The concept is illustrated schematically in Figure 1. The blast hole pattern consists of essentially axial holes bored in a radial pattern. All holes along one "spoke" of the pattern would be drilled to the same depth, with the depth gradually increasing from spoke to

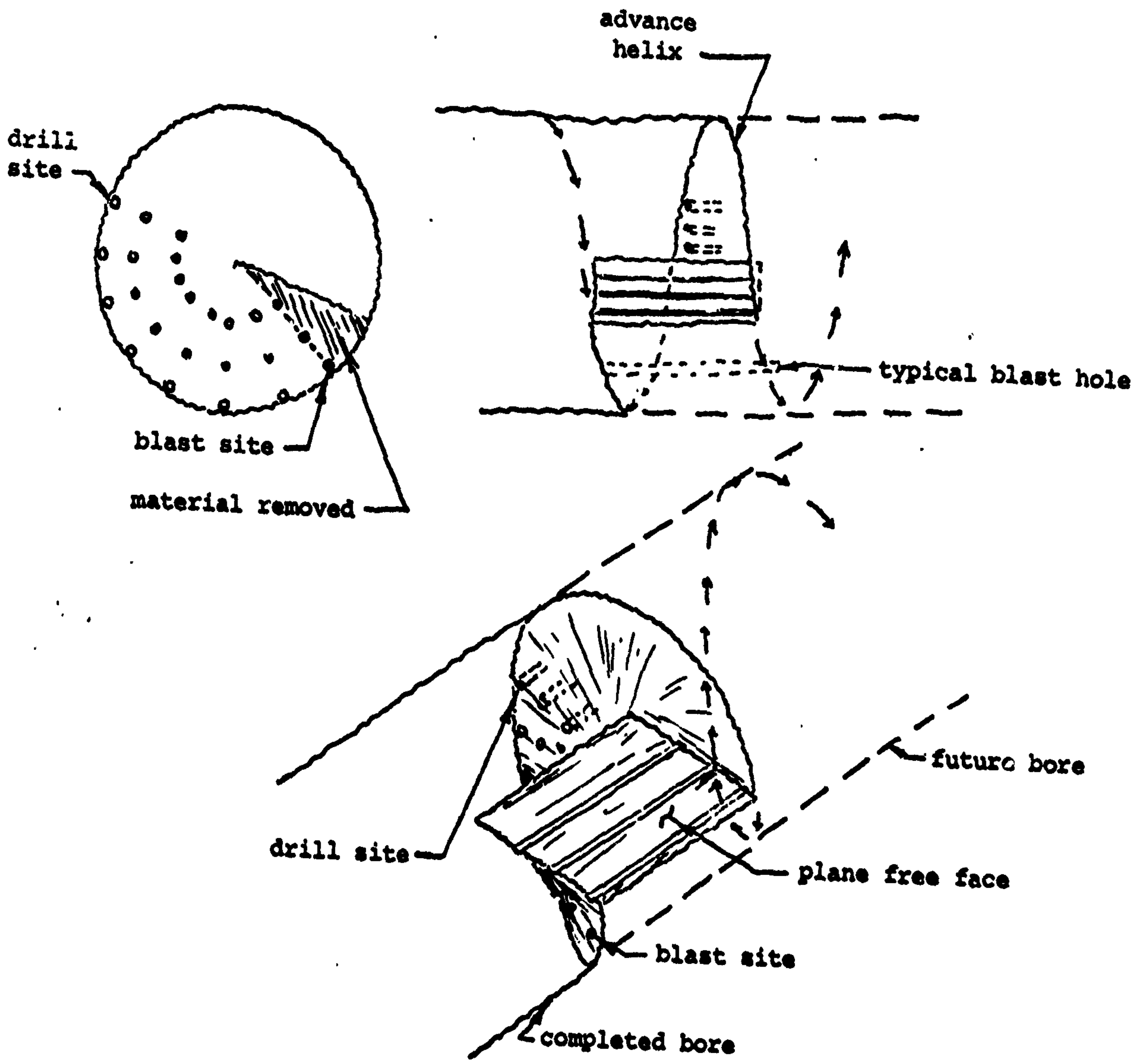


Figure 1
Basic Spiral Blast Hole Concept

spoke. The locus of the hole bottoms at any particular radius would be a spiral.

Explosive is loaded into boreholes along one spoke and shot, thus producing an essentially plane surface, parallel to (and containing) the axis of the tunnel. The next row of holes is then loaded and shot, and so on, with each "pie shaped" section being rather easily removed because of the adjacent free surface. The advancing tunnel geometry will be a combination of a spiral face formed by the hole-bottom distribution (like one turn of a screw conveyor blade) and the intersecting rectangular plane surface. Of course, the outermost boreholes must diverge slightly from the tunnel axis to provide wall clearance for the drill, as in any drill pattern.

In concept the complete machine would employ one or more automated drills, drilling in advance of the loading and shooting position. Drilling equipment and loading equipment would be mounted on a radial arm which may be rotated about the tunnel axis. Mucking would of course occur at the tunnel floor. Mucking equipment can be relatively small since, with nearly continuous blasting, it will never face a large muck pile as occurs with the conventional system.

Shooting sequence can be varied, depending upon rock properties. Perhaps the most logical sequence is shown in Figure 2. Note that only one borehole is fired at a time, with delays between shots to fit ventilation capacity.

Borehole radial spacing would depend upon the burden, i.e., width of the pie segment, and rock properties. Typical practice (5) for cushion blasting, or smooth blasting, suggests a burden-to-spacing ratio

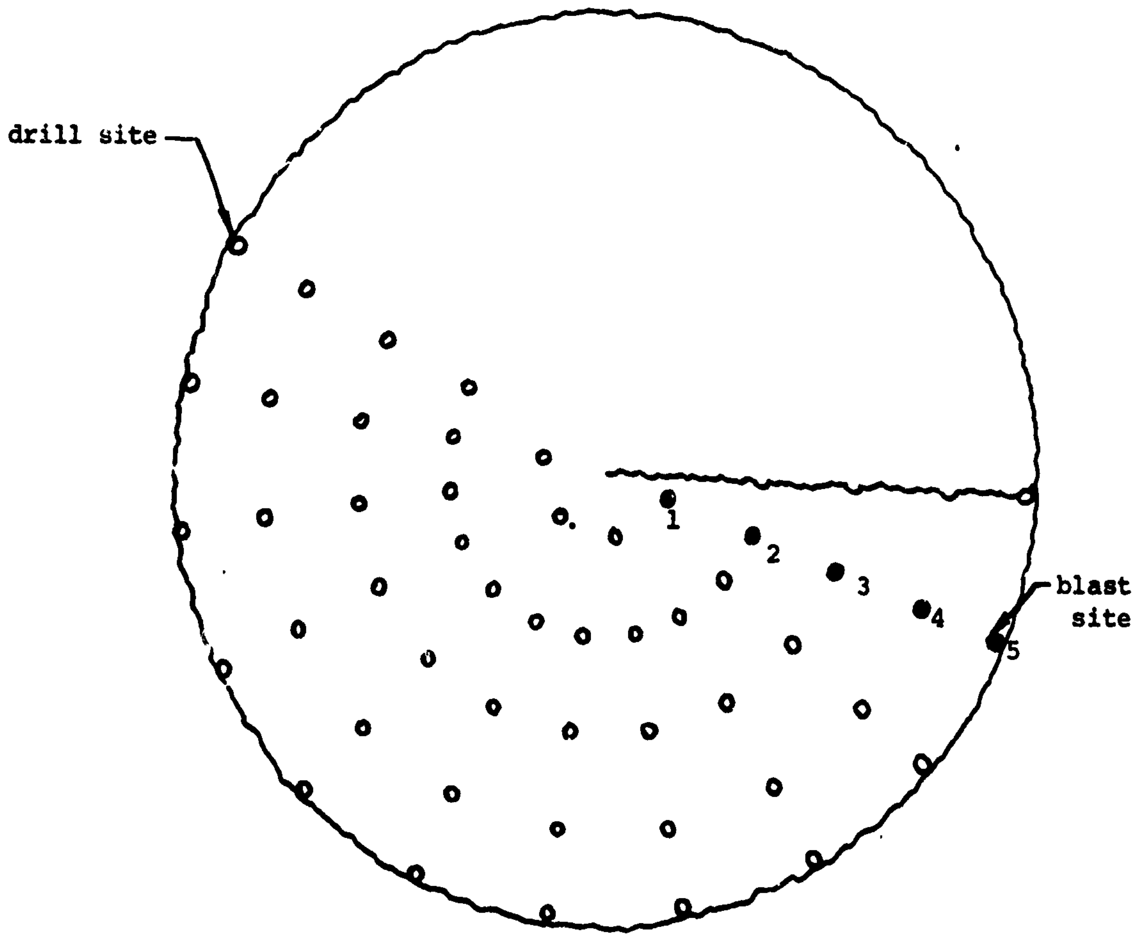


Figure 2
Typical Blasting Sequence

greater than one to produce a reasonably smooth break. However, the spiral blast pattern does not require an extremely smooth break, at least in the radial direction, and wider spacing may be possible.

The final bore wall should of course be reasonably smooth. This can be promoted if necessary by closer hole spacing at the periphery. The pattern also lends itself to a form of pre-shearing as illustrated in Figure 3. The intermediate peripheral holes could be relatively lightly loaded and shot ahead of the "spoke shots" to produce an initial shear between holes, or they may simply be left empty to serve as guide holes for spoke shots. In addition to promoting a smooth final bore, pre-shearing would even further reduce the blast damage to surrounding rock.

Proper blasting practice will of course vary with rock properties, and it may in fact vary significantly from one position to another in a single bore. For example, highly anisotropic rock would respond quite differently as the orientation of the blasting varied from spoke to spoke. However, two relatively general "corner problems" can be identified whatever the rock properties, and proper blasting practice must be found to solve these. The first is in the corner formed between the radial spoke and the outer wall of the tunnel. The blasting sequence illustrated in Figure 2 should alleviate this problem, or pre-shearing, if used, would eliminate the problem. An alternate drilling pattern shown in Figure 4, would simply open the corner angle by bending the spoke near the periphery.

A second corner problem exists at the intersection of the plane

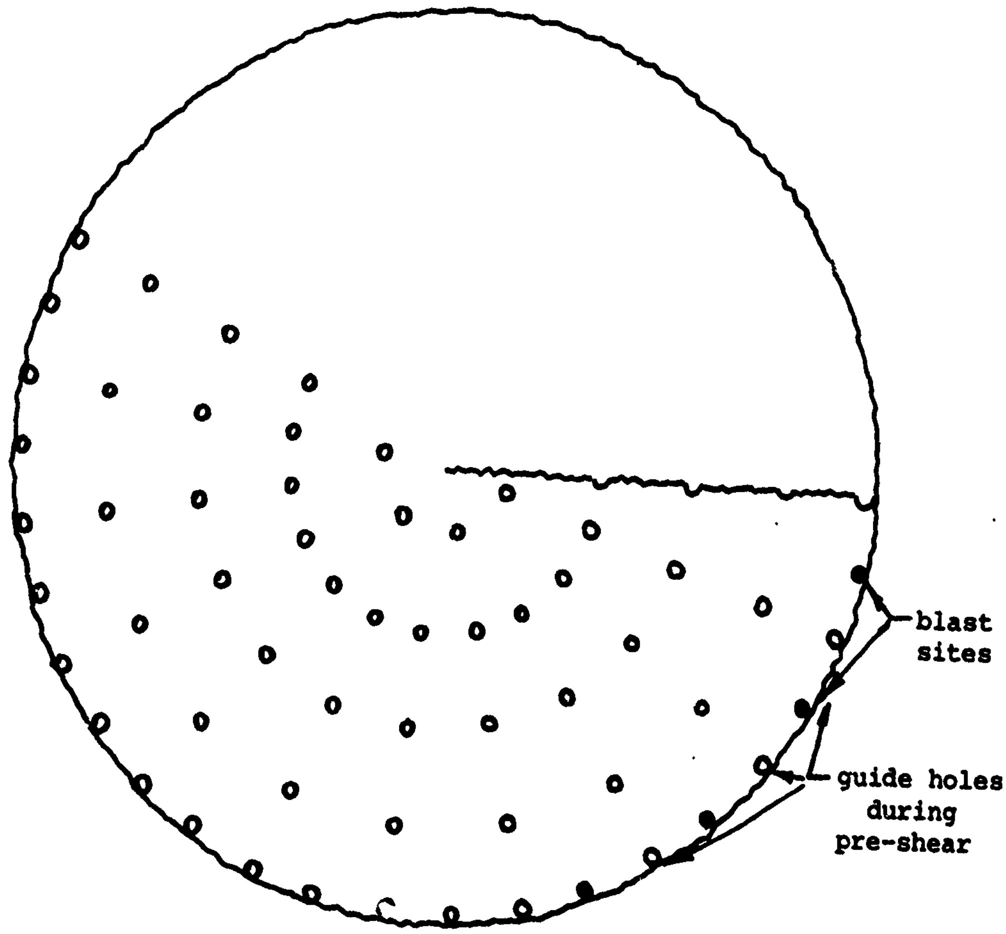


Figure 3
Possible Pre-Shearing Pattern

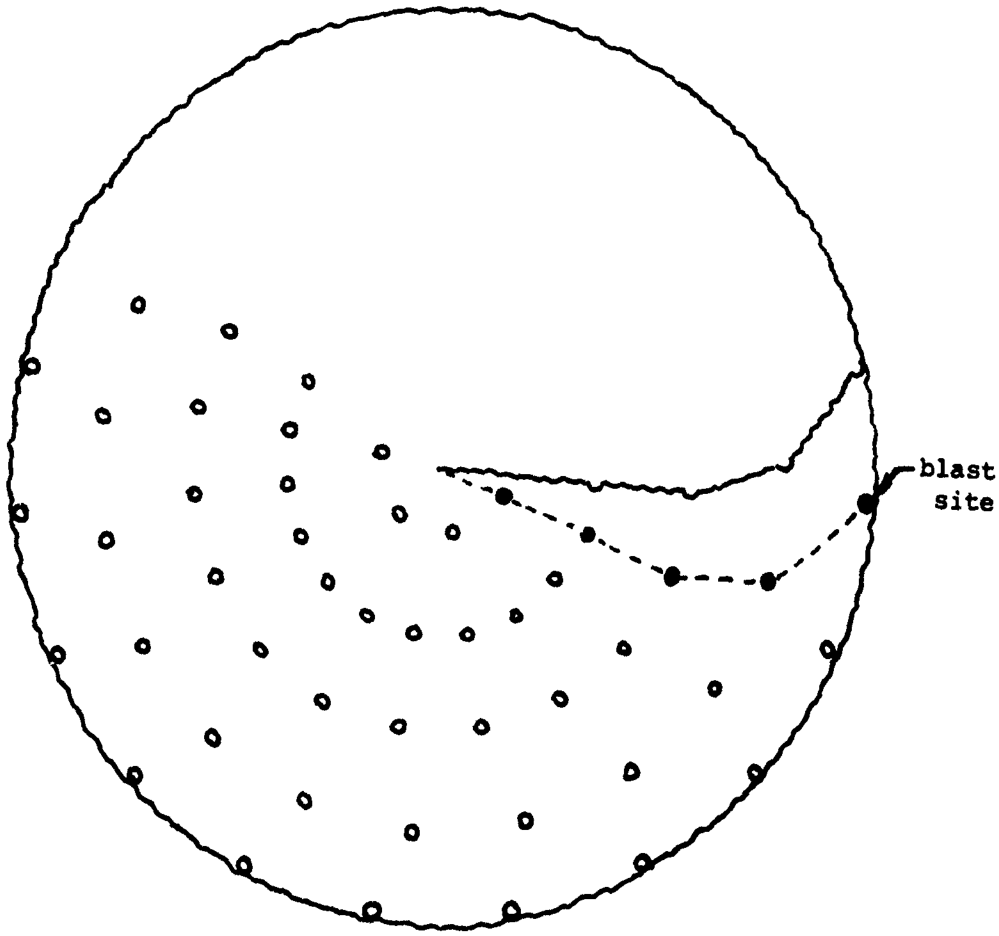


Figure 4
Bent Spoke Hole Pattern to Open Corner

blast surface and the spiral face of the bore. This corner is slightly acute, depending on the ratio of hole length (i.e., spiral pitch) to bore radius. Removal of material in this corner will require that the boreholes extend slightly beyond the intended spiral face, and that the hole bottom be relatively heavily loaded. The remainder of the hole can be very lightly loaded. Actually, model studies show this to be a minor problem except very close to the center of the tunnel (where other considerations solve the problem.)

The clean-cut spiral geometry of Figure 1, with a sharp projection at the center is of course an idealization. The actual appearance would be much rougher than this, and the central projection would never remain standing. In fact, material near the center would be relatively easily removed, and hole spacing can be increased there.

3.3 Advantages of the RAPIDEX Concept

The continuous spiral drill and blast concept should be compared both to conventional drill and blast practices and to present continuous boring practices.

In comparison to conventional drill and blast practice, the spiral blast system offers the following advantages:

1. It is essentially continuous in operation, with associated savings in time and equipment capacity.
2. It is easily semi-automated, avoiding some of the more highly skilled and dangerous labor requirements.
3. It causes little or no blast damage to surrounding rock or nearby structures.
4. The total blasting agent loaded at any one time is drastically reduced.

5. It lends itself to mechanized roof support installation with a minimum of unsupported roof and little or no danger of blast damage to installed supports.

6. No workmen are required directly at the face, except of course for maintenance.

In comparison to continuous boring practice the proposed system offers the following advantages:

1. It offers the economies inherent to drill and blast excavation (without the penalties of cyclic operation.)

2. It can produce any reasonable tunnel shape. Both shape and size can even be varied along the bore if desired.

3. The machinery is composed of relatively standard and low cost elements that can be economically assembled even for short tunnels (and reassembled for different jobs later.)

4. It retains the flexibility of conventional drill and blast techniques in its ability to adjust and continue through whatever conditions are encountered.

5. It is easily maintained, with complete replacement of sub-systems at low cost.

Perhaps the greatest advantage of the proposed system is best summarized in the single word flexibility, whether it relates to varying materials or ground conditions, varying tunnel geometry, or varying job size. In many cases, inflexibility has prevented the application of today's mechanized tunneling methods.

3.4 Brief History of the Spiral Blast Concept

At the initiation of this program it was believed that the spiral blast concept was first conceived by Carl Peterson in 1969 when he was employed by Ingersoll-Rand. Rights to pursue the concept were (and still are) granted to RAPIDEX, Inc. by Ingersoll-Rand in 1971. However, a background patent was soon discovered, Pat. No. 3,098,641, in the name of R. C. Baldwin, assigned to Ingersoll-Rand, and dated 1963. This patent describes the spiral blast pattern, primarily for shaft sinking, but it does not disclose the concept in conjunction with single, small blasts and a shielded machine which stays at the face.

Mr. Baldwin's effort was in response to the need for very large (65 feet in diameter) shafts for Atlas missile silos in northern New York. In this case, although the blast hole pattern as patented was similar, the application of the concept was quite different. Crawler mounted drills were used on the floor of the shaft to drill essentially vertical holes in the shaft bottom, with drilling continuing for an entire shift. In that time a large "pie-shaped" segment, perhaps 90°, was pre-drilled on basically a rectangular pattern. These holes would then be loaded and shot with short delays between rows such that each row blasted to a free face (against which a muck pile would accumulate.) Thereafter, a portion of the muck would be hoisted out, leaving a portion behind for protection of the equipment. The intent was to leave equipment in the shaft during blasting, protected by the remaining muck against the vertical free face. In practice, the contractor chose to hoist his equipment from the shaft anyway for safety.

The pattern worked well, although of the many persons contacted, only the inventor, Ron Baldwin, could recall its use. Note, however, that in such a large diameter with only an 8 to 10 feet advance per revolution, the spiral nature of the geometry would hardly be evident except very near the center of the shaft.

Geometry more nearly like the RAPIDEX concept has been in use in Sweden where it is called the "improved spiral shaft-sinking system". (6) This work appears to have been done in much smaller shafts with a spiral pitch-to-shaft diameter ratio of about 0.6 (the following work assumes 0.5, an easier geometry.) Without automation or continuous advance, an improvement of at least 10 per cent in advance per man shift over conventional pyramid-cut progress was noted.

It is believed that the existence of this work and the background patent will in no way hamper the development of a continuous drill and blast machine based upon the spiral blast pattern. On the contrary, the discovery that the pattern has been successfully used, serves to establish, without doubt, the feasibility of the pattern per se.

4. A Preliminary Blast Geometry

Tunneling machine design problems are of course closely tied to the desired tunnel size and shape. In this case, where the latter were not specified at the outset, it was necessary to select tunnel geometry in keeping with the desired presentation of a typical and reasonable overall design. What is presented here and in the next Section then, is the result of considering a number of different possibilities.

4.1 The Horseshoe Tunnel Section

With an eye to economy in the possible future construction of a prototype machine, attention was focused on rather small tunnel size.. Initially an eight foot diameter round tunnel was considered, round being the simplest possible geometry. Preliminary machine design work within this geometry indicated that, though not impossible, it would be difficult to fit the necessary machine components within the available space. A prototype machine would then be not only uneconomical but, worse yet, difficult to adjust and modify as operating experience with a prototype would almost certainly require.

After considering a range of larger round tunnels, it was decided to return to the smaller section and shift to a horseshoe section. The flat bottom in an 8 x 8 foot horseshoe section seems to provide adequate space for the required machine components. Furthermore this shape, which is of course interesting in its own right, would be more economical both in field tests of the blasting pattern per se (i.e., without automated or prototype equipment), and in prototype development tests. Since the horseshoe section contains both square corners and a circular arc, it embodies all major geometric properties found in round, square and rectangular headings.

Figure 5 illustrates the selected heading geometry including the blast hole pattern suggested as a starting point for field testing. Figure 6 better illustrates the (idealized) three dimensional nature of the spiral face in a horseshoe section for several typical positions of the plane free face. The face model shown in Figure 6 is described in detail in Section 5.7.

The blast hole pattern shown is a compromise between machine design simplicity and the blasting behavior of the rock in question. Design considerations, discussed fully in Section 5.2, indicate that three drills should be used, mounted on a single radial arm, with all three drilling simultaneously. For simplicity of design, the illustrated pattern is made up of two "spoke holes," always 24

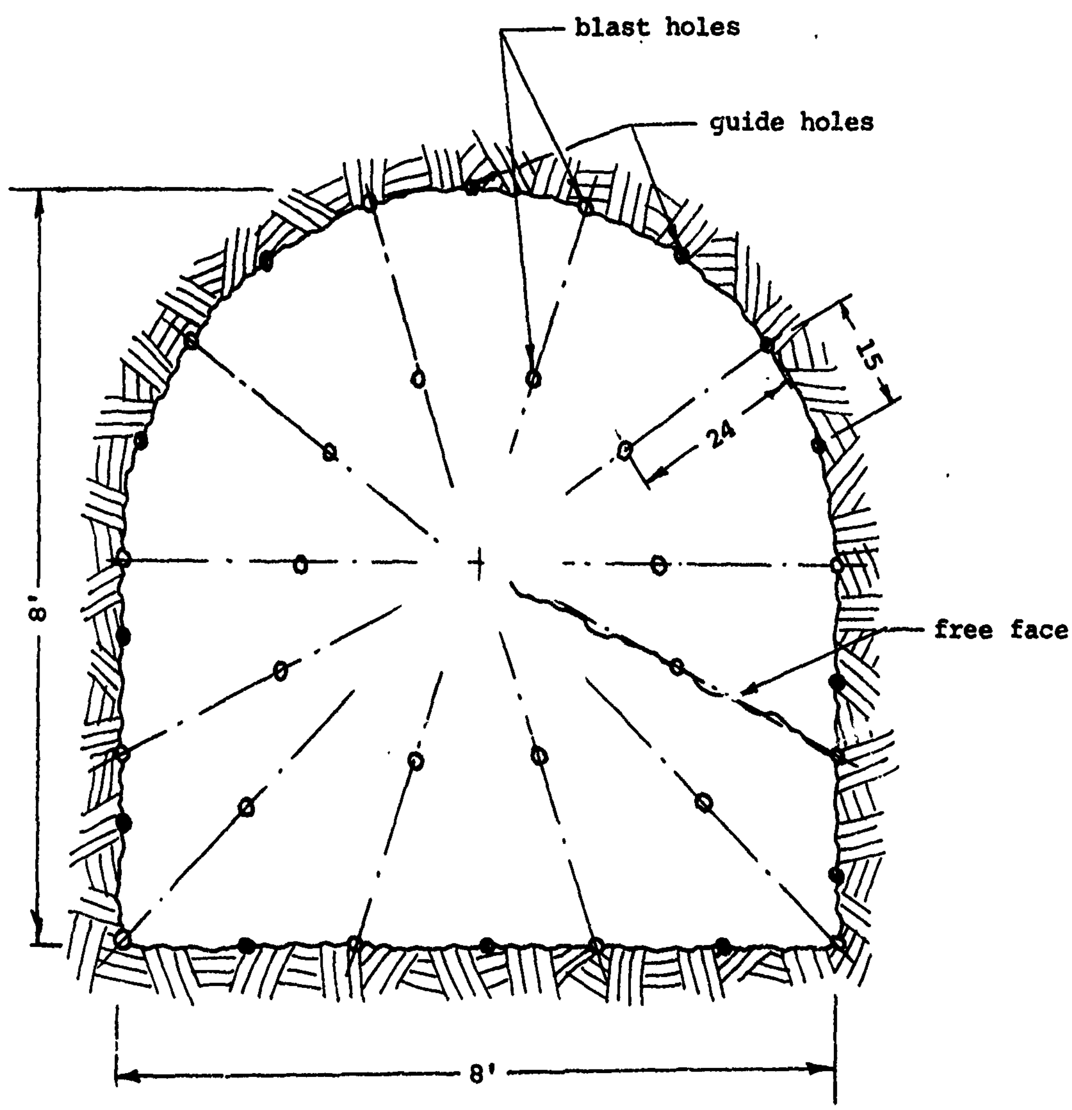


Figure 5

Tentative Horseshoe Tunnel Blast Pattern

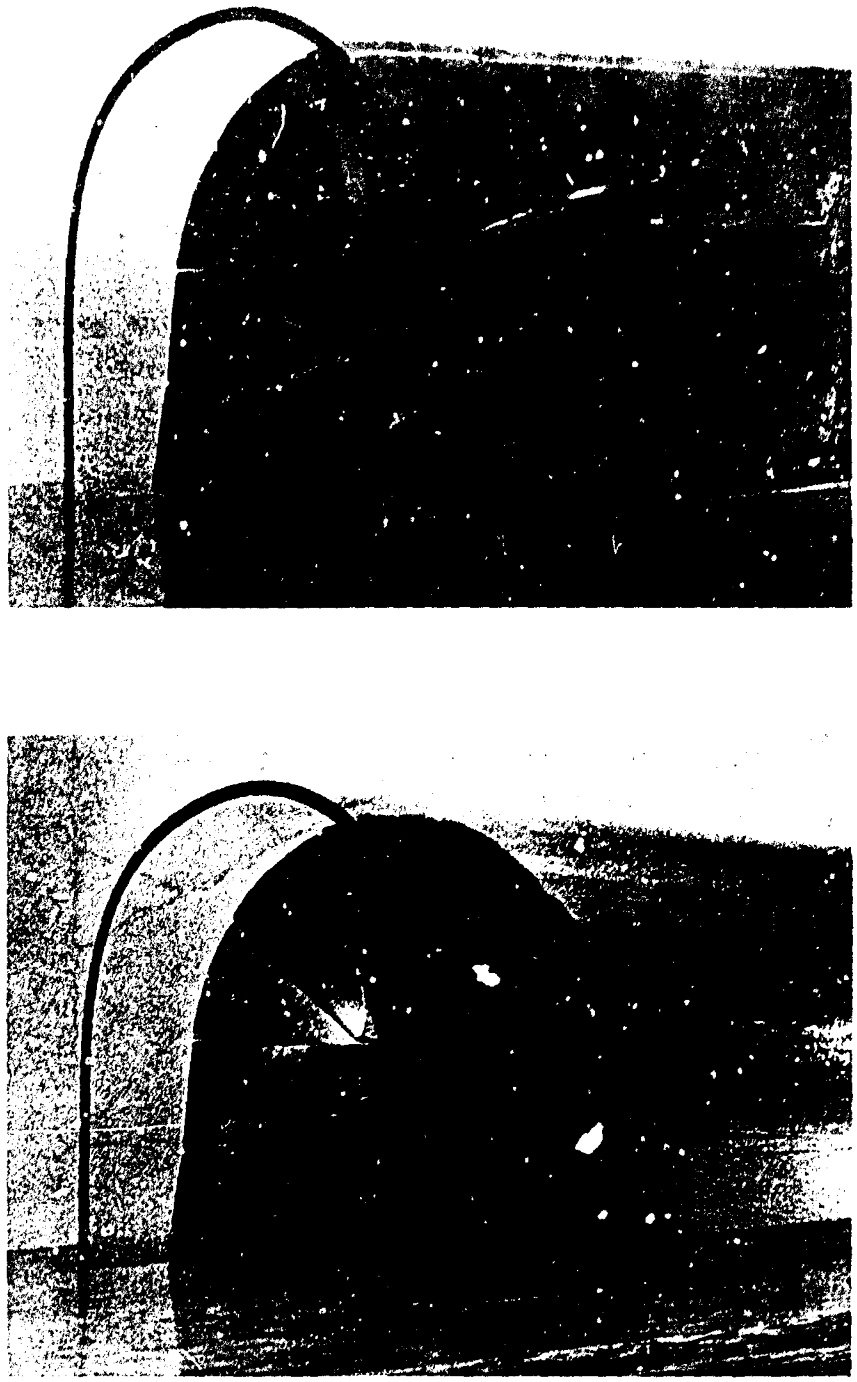


Figure 6

Idealized Spiral Face Geometry

for Horseshoe Tunnel

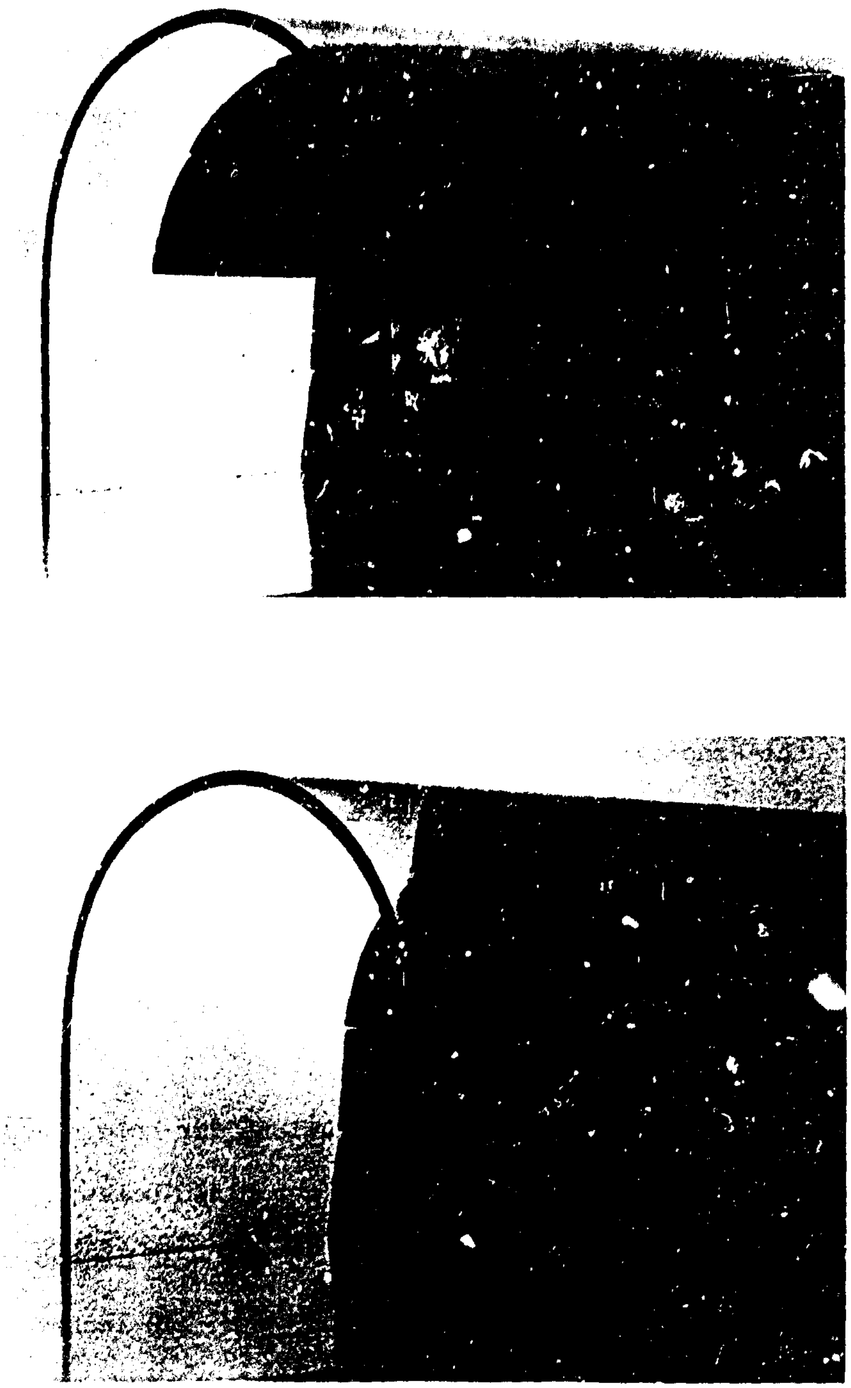


Figure 6

Idealized Spiral Face Geometry

for Horseshoe Tunnel

inches apart, and a single peripheral or guide hole, always 15 inches ahead (i.e., in the clockwise direction) of the outermost spoke hole. The horseshoe section then requires that the radial arm be of variable length, but the distance between drills on the arm need not be variable. Whether or not this simple pattern can be used will depend upon blast requirements (which may vary from rock to rock) as determined ultimately by field test.

4.2 Powder Factor and Hole Spacing

In performing this study, RAPIDEX engaged the services of several experienced blasting experts. The first, Mr. G. B. Terjesen, an employee of Ingersoll-Rand who had examined the concept in 1969, was named in the Proposal as a consultant for the work. In summary, Mr. Terjesen sees no difficulty whatsoever in achieving the desired blast geometry. He notes, however, that firing single shots would be impractical unless automated in view of existing safety regulations for manual loading, shooting, and ventilation. This, of course, was obvious from the beginning.

Mr. Terjesen's specific recommendations for hole spacing and loading are as follows, for 1 1/2 to 2 inch blast holes:

Spacing of peripheral holes	30 - 35 inches
Spacing of internal holes	40 inches
Spacing of pre-split holes	18 - 20 inches

Blasting agent loading, based on 40% nitroglycerin equivalent, would be based on an effectiveness of about 2.1 pounds of explosive per cubic yard of rock or about .9 pounds per ton. Material near the center of the tunnel need not be blasted at all. For example, Mr. Terjesen suggests complete elimination of holes "1" and "2" in Figure 2.

The numbers, particularly the 40 inch internal spacing, characteristic of larger tunnels perhaps, are not directly useful for an 8 x 8 foot tunnel. To obtain the desired spiral progression, we must clearly use a smaller internal spacing. The hole spacing illustrated in Figure 5 was derived in view of these blasting requirements, machine design considerations, and the need for close spacing to match the small tunnel geometry. It is:

Peripheral spacing	24 - 32 inches
Internal spacing	24 inches or less
Guide hole spacing	15 inches or less

The "problem" of close hole spacing and the requisite light loading (see below) is characteristic of small tunnels and not a general property of the spiral blast pattern. Indeed, viewed from another vantage point, that of shield design, light loading is an advantage, not a problem.

A second and more specific, source of expert assistance was found at the White Pine Copper Mine in White Pine, Michigan, where great interest was shown in the spiral blast concept for mining applications. The blast pattern of Figure 5 was examined by several experienced blasting technicians as well as mining engineers, with the conclusion that it would at least provide a good starting point for the necessary definitive field tests.

Experience at White Pine indicates a powder factor of about 0.7

pounds per ton. Based upon this figure, an average hole loading can be estimated. The pattern of Figure 5 contains 24 blast holes. If each is 1 1/4 inches in diameter (a practical size for short holes) and 48 inches deep, total blast hole volume is about 1400 cubic inches. An advance of 4 feet in this heading requires blasting of 230 ft^3 or 20 tons (11.5 ft^3 per ton) of rock. At 0.7 pounds per ton, 14 pounds of explosive would be required. At a density of about 0.04 lb/in^3, an explosive volume of about 350 in^3 or only about one quarter of the available hole volume is required. Lower explosive densities can be used to better utilize the blast hole volume. This should create no serious problems with conventional explosive agents. Furthermore, the pumpable explosive agents contemplated for automated loading can be tailored to a wide variety of properties to fit these requirements. Note again, however, that this potential problem is peculiar to small tunnel sections, not to the spiral blast pattern in general.

Powder factor is a function of blast geometry as well as explosive and rock properties. In using this powder factor we have in effect assumed that the effectiveness of the spiral pattern will be the same at that conventionally used at White Pine. Ron Baldwin, the original inventor of the spiral blast pattern, suggests that significantly reduced powder factors, perhaps by as much as half, can be expected because of the free surface adjacent to each blast. This may be true in large tunnels, but within a 8 x 8 foot heading, a significant strengthening effect can be expected from corner effects. At present then, there seems to be no justification in assuming any substantial increase or decrease in powder factor.

The second step in estimating blasting performance is to estimate the rock excavated by each shot in the pattern. In general, the pattern would be adjusted on the basis of such an estimate in an attempt to achieve uniformity. In this case, however, some nonuniformity may be acceptable in view of the perhaps conflicting requirement to use a simple, easily automated pattern.

Figure 7 is an attempt to estimate the distribution that would result from the pattern of Figure 5, fired in clockwise sequence with the innermost hole on each spoke fired first as shown in 7a.

Figure 7b is a plot of the estimated tonnage per shot, assuming a 4 foot advance per revolution of the pattern. Of course, this estimate cannot be highly accurate, but the results seem to indicate about .9 to 1.0 tons per shot for the outer holes and .7 to .8 for the inner holes. Thus, .6 to .7 pounds of explosive would be required in the outer holes and .5 to .6 in the inner holes.

Some nonuniformity, as might be expected, is seen in the corners. Figure 8 represents a variation in which holes A and B (Figure 7) are not loaded and the firing sequence is varied in the corners as shown in 8a. Figure 8b indicates some improvement, although two of the inner holes must now be loaded to the higher level.

In both patterns, material near the center is not blasted directly. This material will be easily broken and it is expected that axially extending central material will never develop.

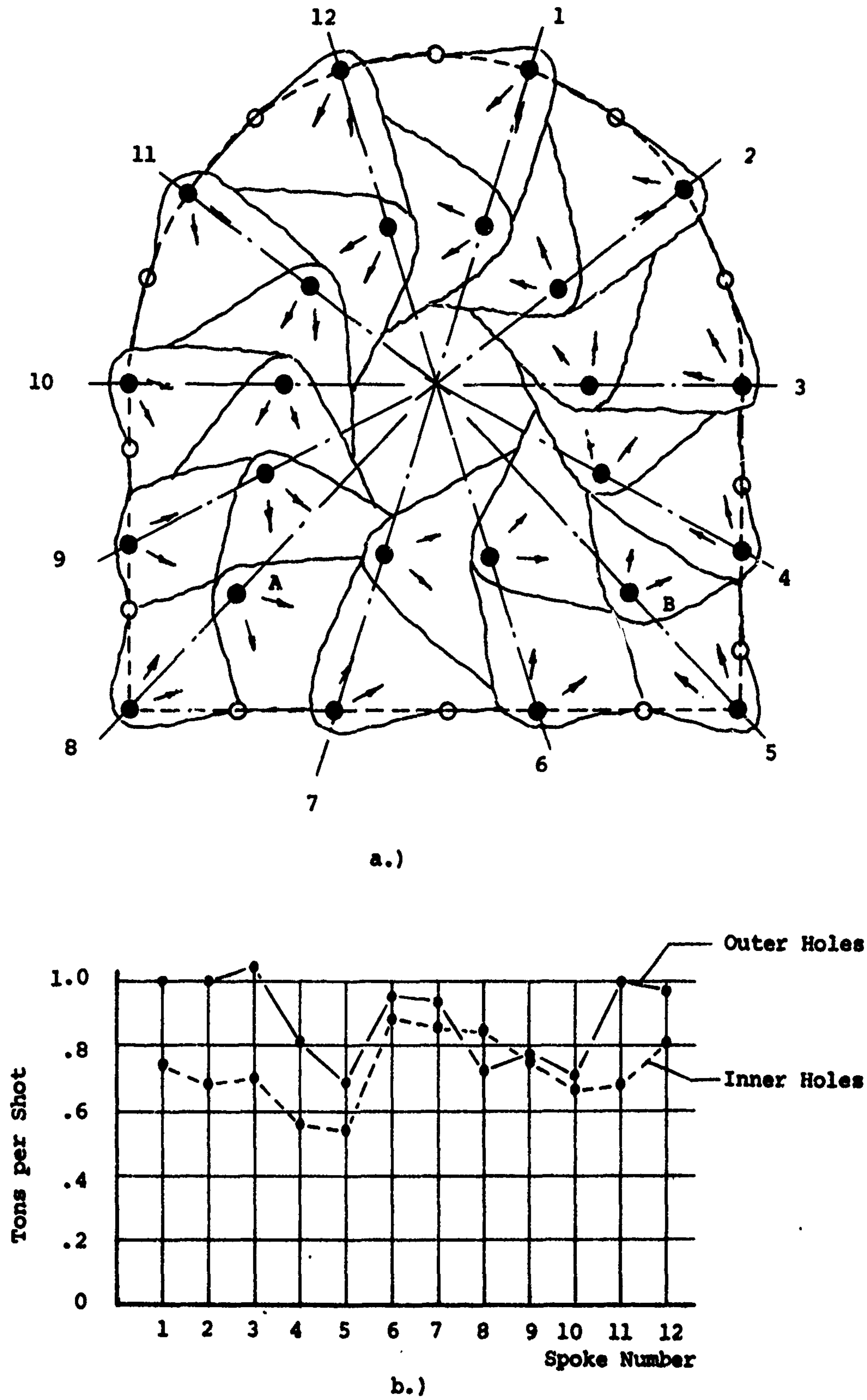
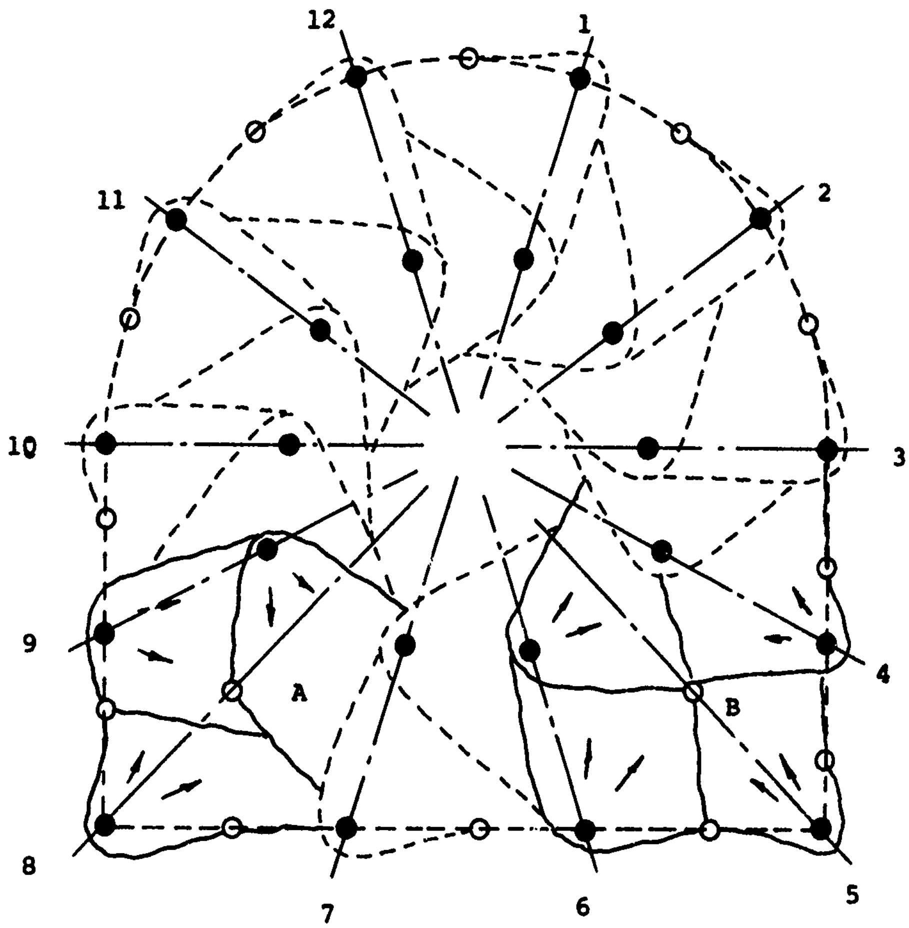


Figure 7

Blast Distribution Estimate



a.)

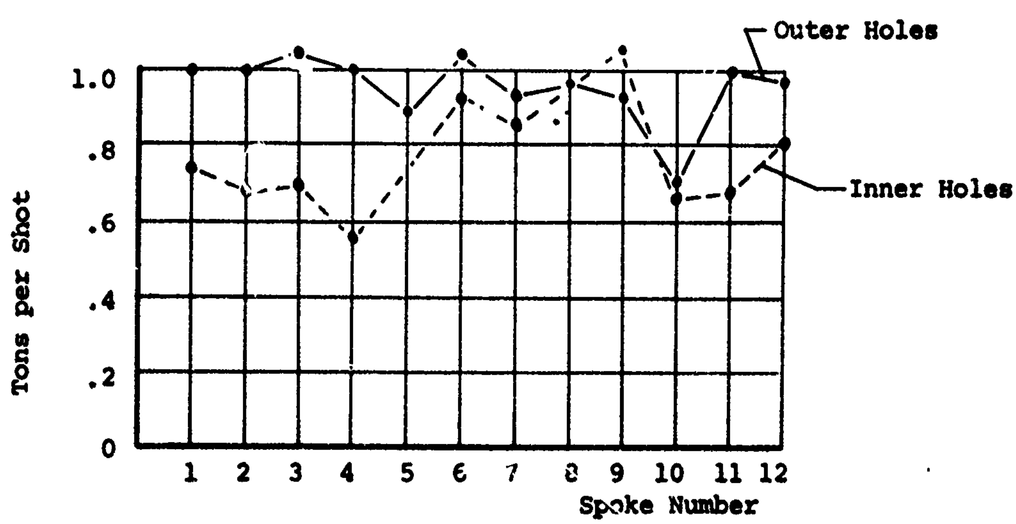


Figure 8

Modified Blast Distribution

At this time it is believed that this pattern represents a reasonable starting point and that, within the accuracy of such estimates, no further refinement on paper is justified. The ultimate refinement must come through field testing (wherein the reasonable restraints of design requirements must be kept in mind.)

4.3 Ventilation Requirements

At the outset it seems clear that machine operators cannot be allowed to stand in the open in the vicinity of this or any other continuous drill and blast tunneling machine. There would be danger from flying rock, intolerable noise, and danger from toxic fumes. The operator(s) must be enclosed in life-support cabs or, preferably, removed entirely from the danger zone, operating the machine by remote control with closed circuit TV monitoring.

It is interesting, nevertheless, to examine the ventilation requirement if, following present regulations, breathable air is to be maintained at the face. A Fume Class 1 explosive can be presumed to generate .0163 ft^3 of toxic fumes per cubic inch of explosive. If this must be reduced to 25ppm, then 652 ft^3 of air must be used to dilute the fumes from each cubic inch of explosive. From the previous section, each blast hole will contain 350/24 or about 14.6 cubic inches of explosive, requiring 9500 ft^3 of air. Blasting rate will depend upon a host of machine design considerations, but in Section 6 it is estimated that it may be one shot every 45 seconds. Then 9500/.75 or 12,700 cfm of ventilating air would be necessary. That would require a 5 mile per hour wind in the tunnel if half the tunnel were used for inflow and half for outflow. Other interpretations of toxicity limits may require dilution to 5 ppm, or five times this ventilation flow.

If we can avoid toxicity problems by enclosed or remote operation it will still be necessary to ventilate to maintain visability. For this purpose a 10:1 dilution of all fumes should be adequate, particularly in view of TV monitoring with capabilities to see through smoke. Total fume generation is about 1000 times the volume of explosive. With the previous numbers, then, total fume generation rate will be about (1000x14.6)/(.75x1728) or 11.3 cfm. Ventilation air would than be required at 113 cfm, a very small rate. Actually, considerably more than this could easily be provided.

In order to direct the air at the face to assure good visibility, blowing ventilation should be used, at least at the face. Suction in the exhaust path may also be desirable, depending on other activities that may be in progress behind the tunneling machine or at the portal.

5. Preliminary Machine Design

The spiral drill and blast machine has a variety of sometimes conflicting functions to fulfill, all within limited space adjacent to an unusual tunnel face geometry. It can be appreciated, then, that there is considerable interaction between the various machine components even though, for clarity, they are discussed separately in the following subsections. For example, mucking sequence as related to drilling, loading and shooting operations dictates the space available for the latter functions. This in turn influences the position of the drills relative to the shooting position which, again in turn, influences the position and shape of the shield. The preliminary design described in the following, therefore, is the culmination of quite a series of trial arrangements in search of the best overall combination.

5.1 Overall Design

Figure 9 illustrates the general layout of a spiral pattern, continuous drill and blast tunneling machine. It is a crawler mounted unit, carrying a rotating radial arm at the front which in turn carries drilling, loading, and initiation equipment. A scoop pulls muck from the face area to an apron, thence up to a central conveyor which discharges at the rear of the machine.

Service lines, perhaps including air, hydraulic fluid, water and explosive(s), enter at the rear of the upper box-beam frame member. They are carried inside this member to a rotary union (see following subsection) and into the rotating radial arm. In this way the lines are entirely enclosed and protected.

Note that, except for automated loading and initiation devices, standard, commercially available, components can be used throughout. Separate components and functions are treated in the following subsections.

5.2 Drilling

Ordinary percussive drills are used, mounted on a rotating arm at the front of the machine. In keeping with the blasting requirements described in Section 4, the smallest convenient drill diameter would be used.

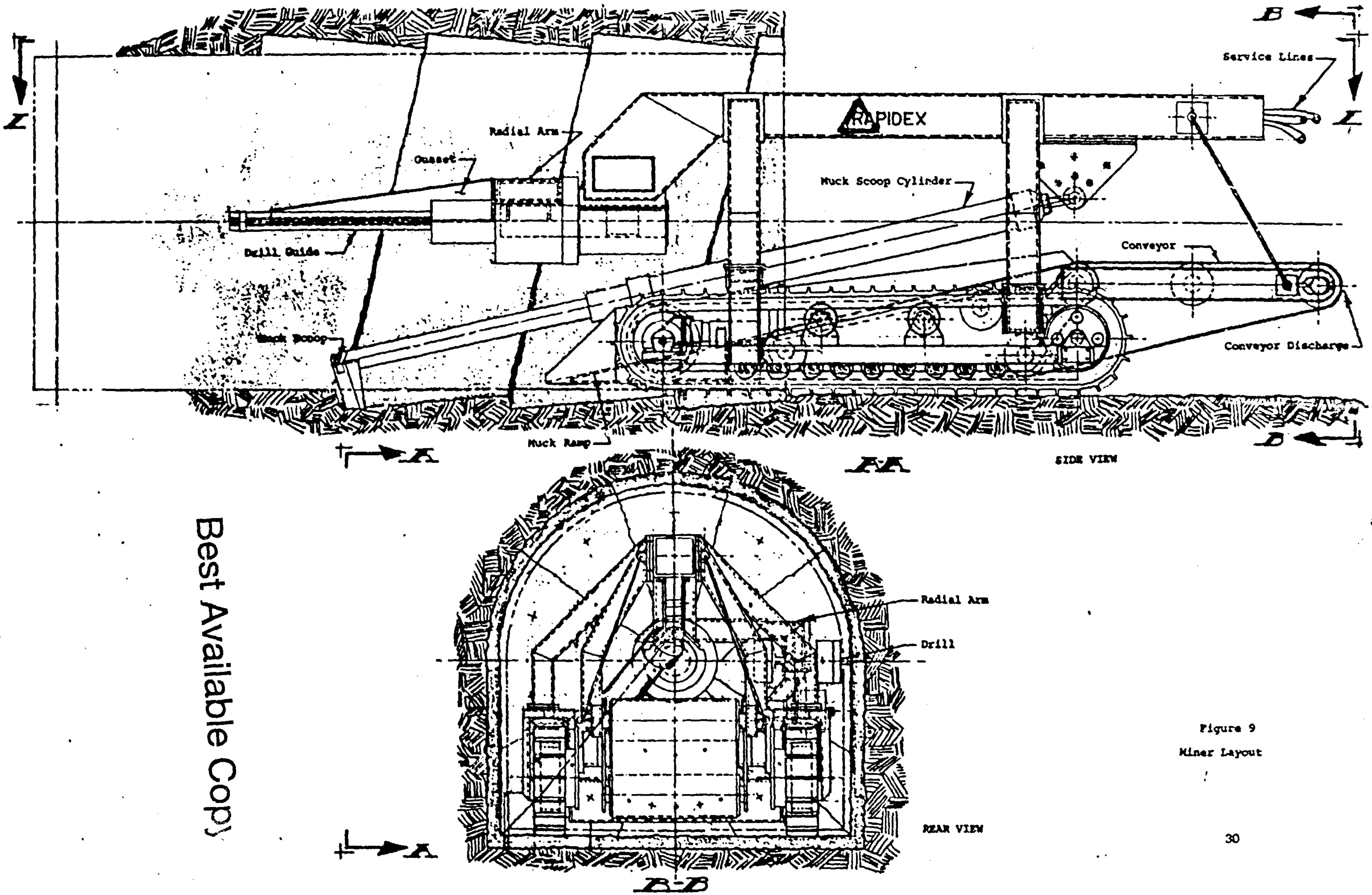


Figure 9
Miner Layout

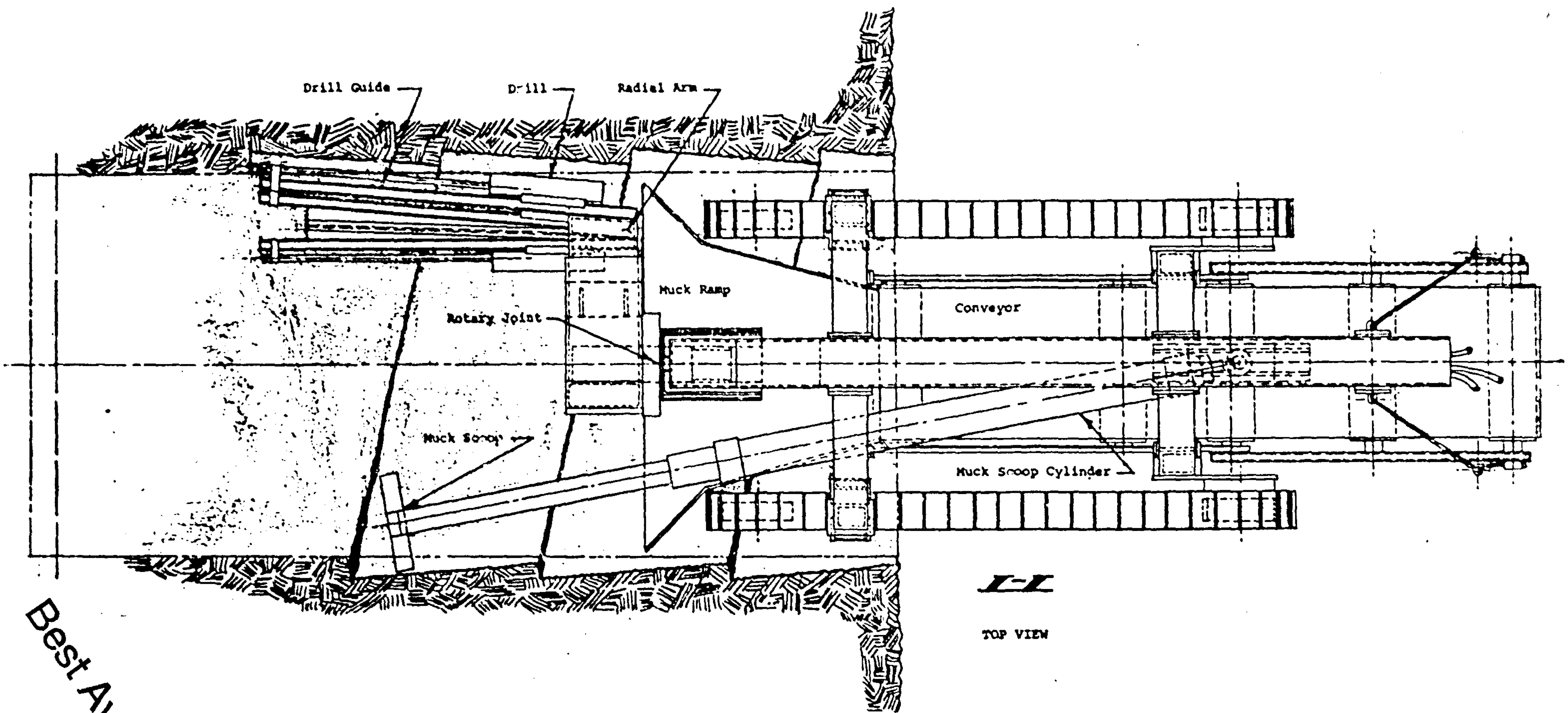


Figure 9

Miner Layout

For the suggested drilling pattern in an 8 x 8 foot horseshoe heading three drills would be used. Two "spoke" drills would be mounted (approximately) along a radial line as shown in Figure 10. These drills would remain a constant 24 inches apart. A third drill for the peripheral guide hole would be mounted a constant 15 inches from the outer spoke drill.

Means would be provided to vary the angle between the radial direction and a line between the two peripheral drills so that the latter can both remain on the periphery for all positions of the radial arm. Figure 10 suggests a separate pivoting bracket carrying both peripheral drills to provide this adjustment. Pivoting could be manually (remote) controlled or automatically accomplished in response to radial arm position by means of a push rod acting on a simple, non-rotating cam mounted at the center of the assembly.

Percussive drills (i.e., drifters) would be carried on conventional guides, and advanced into the face by conventional chain or screw feed mechanisms. Since 48 inch deep holes (or a little more) are anticipated, 60 inch drill steel could be used. The guide then would be about eight feet long - rather short in comparison to normal practice.

The inner spoke drill can be mounted parallel to the tunnel axis, but as is normal practice, the peripheral drills must be mounted at a slight angle to the wall to provide clearance for the drifter as the hole reaches full depth. Examination of the drilling pattern of Figure 5 shows that the peripheral spoke drill must

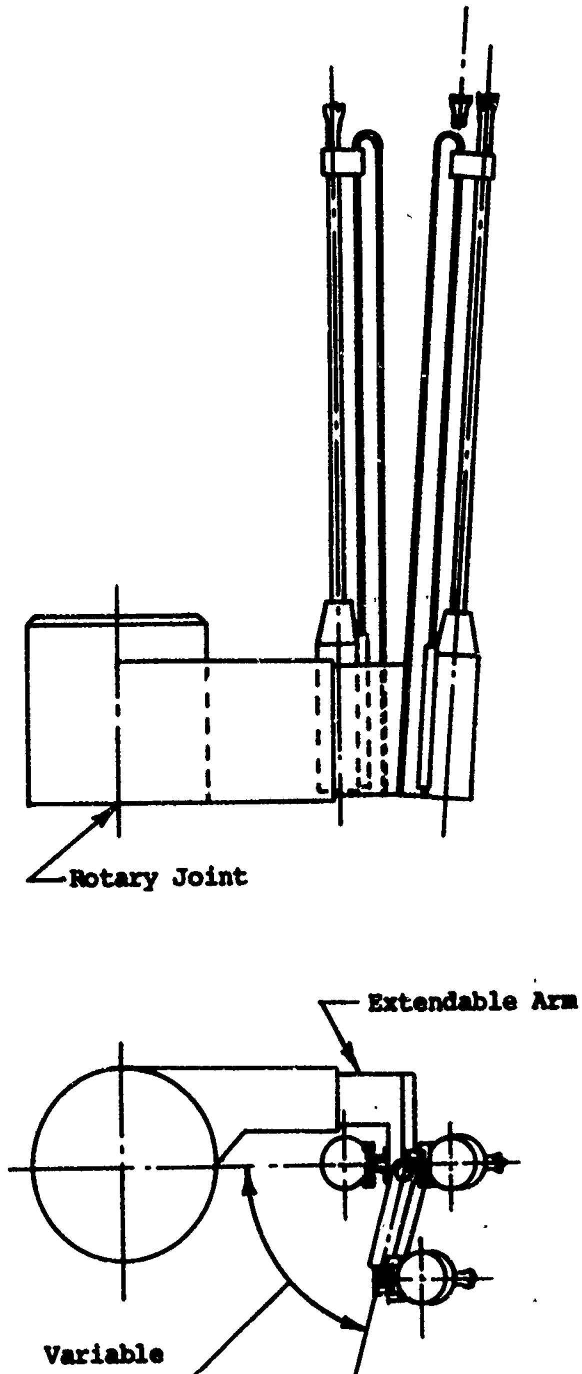


Figure 10
Rotating Drill Mount Arm

operate in both lower corners of the face while the guide hole never occurs in a corner.

This particular layout was derived in an attempt to avoid, as much as possible, the necessity of relative motion between the separate drills on the rotating arm. Only the angular position of a pivoted bracket is varied, and that can easily be accomplished by a cam. The radial arm is moved in and out to produce the rectangular lower portion of the tunnel section (or any other reasonable shape for that matter.)

This simple motion appears to create a reasonable blast hole pattern, but, clearly the pattern must be verified by actual test. Such tests may indicate that pattern adjustments are necessary but, unlike ordinary blasting practice, such adjustments must consider both the blasting performance and the ease with which the pattern can be produced by a reasonably simple drill positioning mechanism.

Throughout this discussion a fully rotating assembly has been implied. From an operating standpoint this would be the best and most elegant approach, allowing uninterrupted progression of the blast spiral. However, this approach does require a rather complex rotating joint between the machine and the rotating arm. This joint would be required to carry air, at least one pair of hydraulic lines, water (for hole flushing) and, possibly, a pair of explosive component lines if, for example, explosive sensitization were to be accomplished outside the main body of the machine* In addition, electrical lines to control various

*Since the orientation of an explosive injection system about its own axis is not important, it would be possible to carry the two explosive components through a pair of flexible lines without a rotary joint.

fluid powered systems on the rotating arm (drill feed motors for example) would be necessary if a multiplicity of separate fluid lines is to be avoided.

An alternate scheme, much closer to conventional practice, would use a reversing drill arm assembly, thus avoiding all rotary joint problems at the expense of a very slight delay in progress. Starting at the top of the tunnel section, the drill assembly would rotate (clockwise) for 360 degrees to produce one complete revolution of the spiral pattern. The assembly would then be reversed to travel back (without drilling) to its starting point and the sequence repeated. This motion could be accomodated by a bundle of flexible lines (fully protected within the framework) without rotary joints. Valving of all fluid lines could then occur on the stationary machine reference frame.

Reversal should occur at or near the topmost position to assure that the assembly is unencumbered by blast fragments at the time. A satisfactory mucking sequence can be built around this motion.

The delay in such motion would be only that required to rotate the assembly 360 degrees - less than one minute in an eighteen minute or more cycle. Thus, at least for prototype construction this seems to be the best approach.

The foregoing assumes pneumatic drifters of the size and performance available today. Probably by the time a prototype machine can be constructed, and certainly by the time it is fully developed, hydraulic drifters will be available. Their primary advantage, low noise, is of no consequence in this case, but they would nonetheless be advantageous in that they would provide higher performance and require less space. Space savings would occur both at the drill position on the rotating arm and in the bundle of fluid lines carrying power to the drills.

5.3 Explosive Loading and Initiation

Work on this important aspect of the development has been carried out at the Pittsburgh Mining and Safety Research Center (1). That work has now been terminated in a less than completed state, but a number of satisfactory explosive agents and a satisfactory initiation technique have been identified. Equipment to accomplish loading and initiation has not been designed but, for the present, we are assured that such equipment will be no more bulky than the drilling equipment.

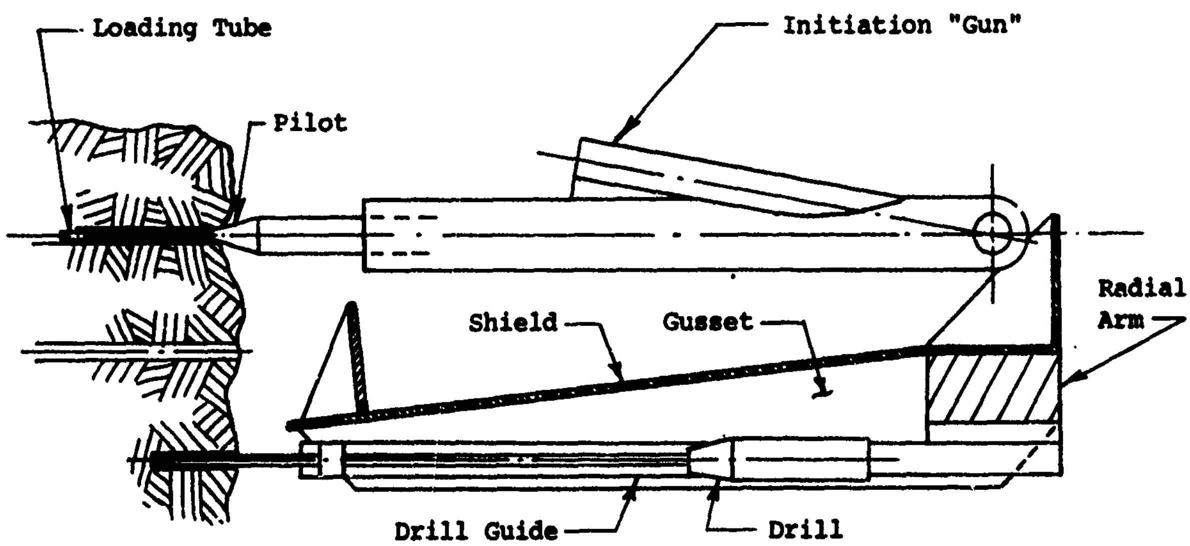
A number of two-component slurries and gels are possible in this application. For safety, the components would be separately pumped to the face and mixed upon injection. To assure proper loading, the mixed explosive would be injected through a tube extending into the blast hole and withdrawn as injection proceeds. Tube injection would also serve to detect incomplete or damaged blast holes.

It is possible, though by no means certain, that low density explosive formulation to match the required low powder factor may result in a relatively insensitive (to initiation) mixture. If necessary, then, the formulation can be varied to leave a sufficiently sensitive material at the outer end of the explosive column.

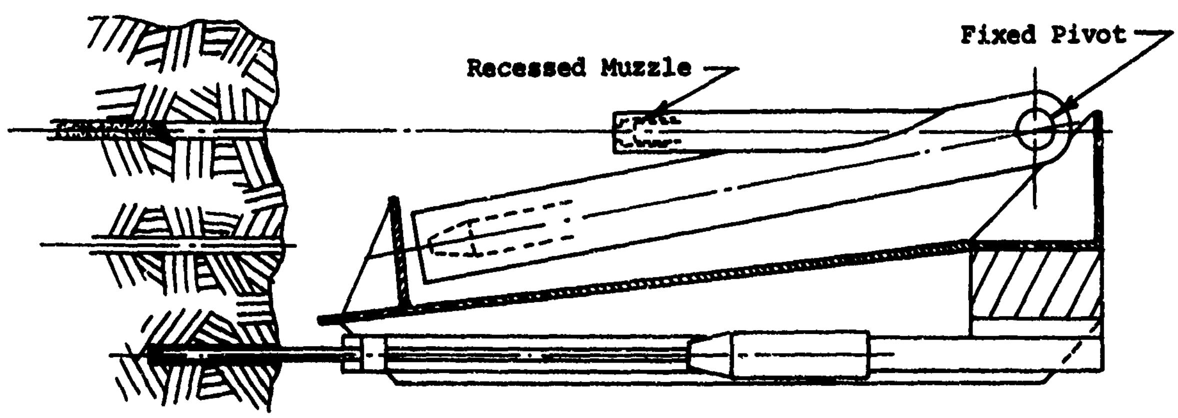
A number of initiation techniques was studied with the conclusion that projectile impact would be the best method for an automated loading and initiation system. Reasonably low projectile velocities (of the order of 1000 feet per second) are effective and perhaps even standard .22 caliber ammunition could be used. Gunpowder in some standard cartridge form represents an obvious projectile propellant system, but it is also believed that a satisfactory compressed air (or compressed hydraulic fluid for that matter) gun can be developed.

Figure 11 illustrates a possible design for loading, initiation, and shielding components. The loading and initiation components would be supported from the same radial arm that carries the drills. Loading and initiation would occur two spokes behind the drilling operation (see Section 5.5 on mucking for a discussion of spacing requirements.)

Angular position of the loading mechanism would be adjustable relative to the drilling position to assure accurate alignment with the desired borehole. A heavy pilot extends from the front of the loading cylinders to fit within the borehole, as shown in Figure 11a. When so inserted, the loading assembly is locked in position. The injection tube is then inserted to full depth and withdrawn as explosive is injected. After injection and without releasing the locked position, the assembly is pivoted to the position shown in Figure 11b. The loading cylinder is thereby moved to a safe position while the initiation "gun" is aligned with the borehole. The



a.) Loading Position



b.) Initiation Position

Figure 11

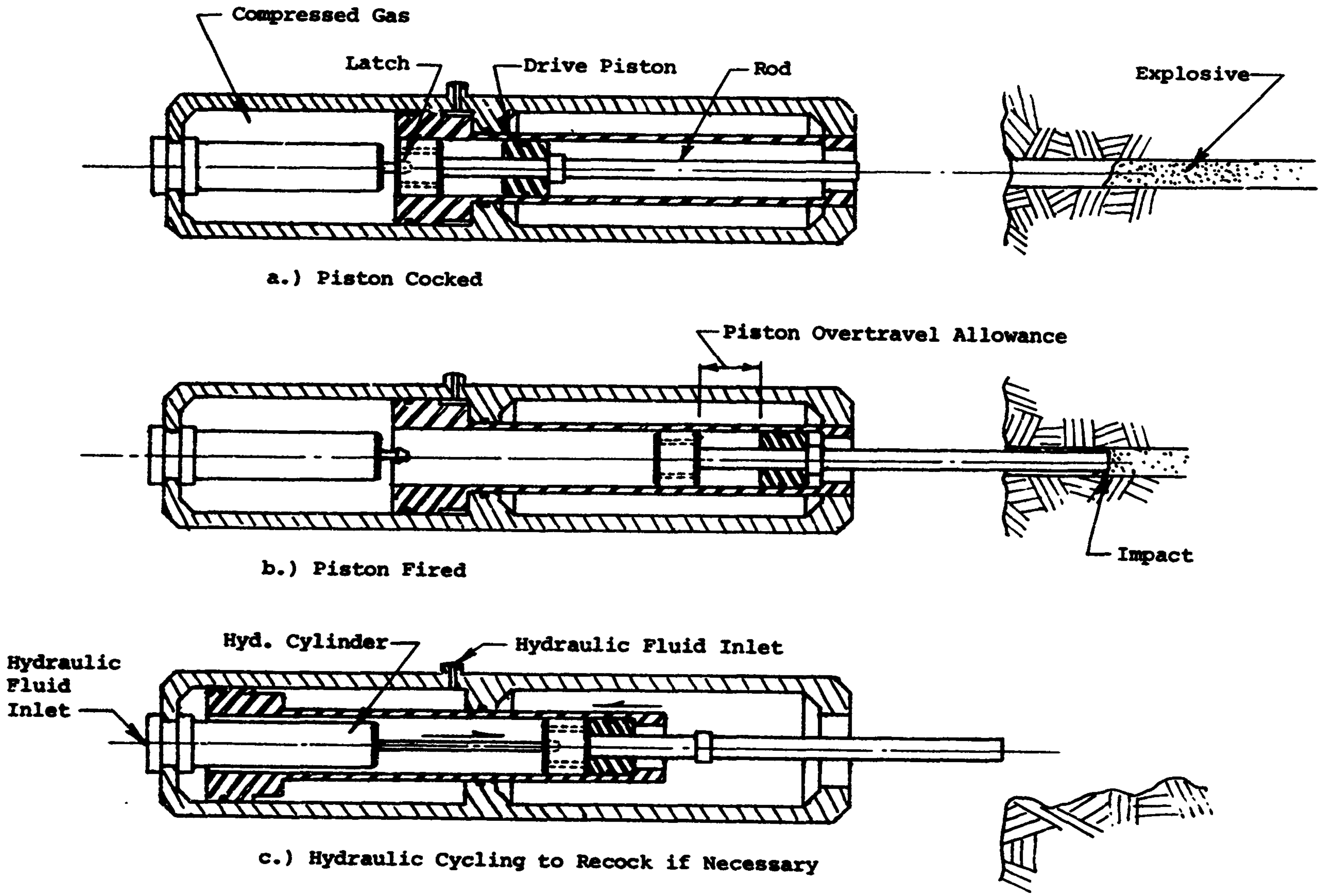
Loading, Initiation, and Shielding Concept loading cylinder would be of heavy sidewall construction while its end would fit behind a protective shield protrusion as shown. In the position shown in Figure 11b the initiation gun is fired directly into the loaded borehole.

Initiation by projectile impact does not permit stemming the loaded borehole. This may lead to lower than anticipated blasting efficiency. In the course of this study a combined initiation and stemming device was conceived as illustrated in Figure 12.

In essense this device hurls a relatively massive steel rod into the borehole where it impacts the explosive surface. The rod would be propelled by compressed gas acting over a reasonably long stroke (say one foot) to velocities of the order of several hundred feet per second. As shown in these sketches, the rod is driven by a relatively large diameter piston to achieve the desired acceleration at reasonable drive fluid pressures. Upon initiation of the explosive, the much higher explosive pressure, acting for a short duration on the smaller rod diameter, would hurl the rod back against the compressed gas, cocking the device for the next hole.

It is conceivable that the high energy of a massive rod at moderate velocities could directly initiate the explosive, but at present this seems unlikely. It may be necessary to place an impact sensitive material on the tip of the rod or on top of the explosive column to achieve initiation.

The mass of the rod acting as stemming would improve both blast effectiveness and initiation reliability. At present, however, borehole pressure-time histories are not available to determine the feasibility of the concept. Further, although the design of Figure



a.) Piston Cocked

b.) Piston Fired

c.) Hydraulic Cycling to Recock if Necessary

Figure 12
Combined Initiation and Stemming Concept

12 is such that deformation of the rod tip is not critical, it is not known what errosion and other tip damage will occur.

5.4 Shielding

Proper shield design is critical to the success of any continuous drill and blast concept. What is in fact proper will depend upon blast action and it is clear that shield design cannot be accomplished without field testing of the blast pattern. The following then, represents thinking at this point in keeping with design limitations imposed by space and the requirements of other machine functions.

Figure 11 illustrates a shield consisting essentially of a flat plate extending over the drifters and guides. At the time of blasting it is below the blast site and most blast fragments will be thrown directly away from the shield. Shield width would be just wide enough to protact the drills, leaving the center region open to promote easy muck movement in this area.

Loading and initiation equipment is mounted above the shield to avoid the necessity of a moving shield and to assure good visibility when aligning the load cylinder with the selected borehole. Sides of the load cylinder would be of heavy, self-shielding construction while, at the time of blasting, the nose of the load cylinder would be protected by the stationary shield. The initiation "gun" would be heavily shielded and sufficiently removed to minimize damage from small fragments traveling directly into its muzzle.

5.5 Mucking

In comparison to conventional drill and blast techniques, the proposed continuous technique greatly reduces the required mucking capacity. Mucking will occur as a continuous low level, rather than occasional high level, activity.

Blast fragments will be of irregular shape and size and, furthermore, the tunnel floor will be an irregular blasted surface. These features combine to make simple automated mucking difficult. For the present then, a simple, manually controlled scoop, shown in Figure 9, pulls muck onto an apron at the front of the unit. From there it is carried by belt conveyor to the rear of the unit.

Mucking action then is much like that of a slusher in terms of ability to handle a wide range of muck properties. The scoop drive, instead of by cable, is by a non-rotating extension from an hydraulic cylinder. Scoop action would be much like that of a "Gradall" but a much smaller unit would suffice. In fact, the non-rotating, hydraulic, extendable boom used on portable drill mountings would be an ideal component for a prototype scoop drive.

Mucking sequence, as related to the position of the rotating drilling, loading, and shooting equipment, is shown in Figure 13. Starting with Figure 13a, showing the rotating equipment (cross-hatched area) in the upper right quadrant, the free face would be near vertical and blasted material would fall freely to the floor in the lower left quadrant. The muck scoop has freedom to work in this corner or all across the floor for that matter. This condition prevails until the free face is at or below horizontal, as shown in

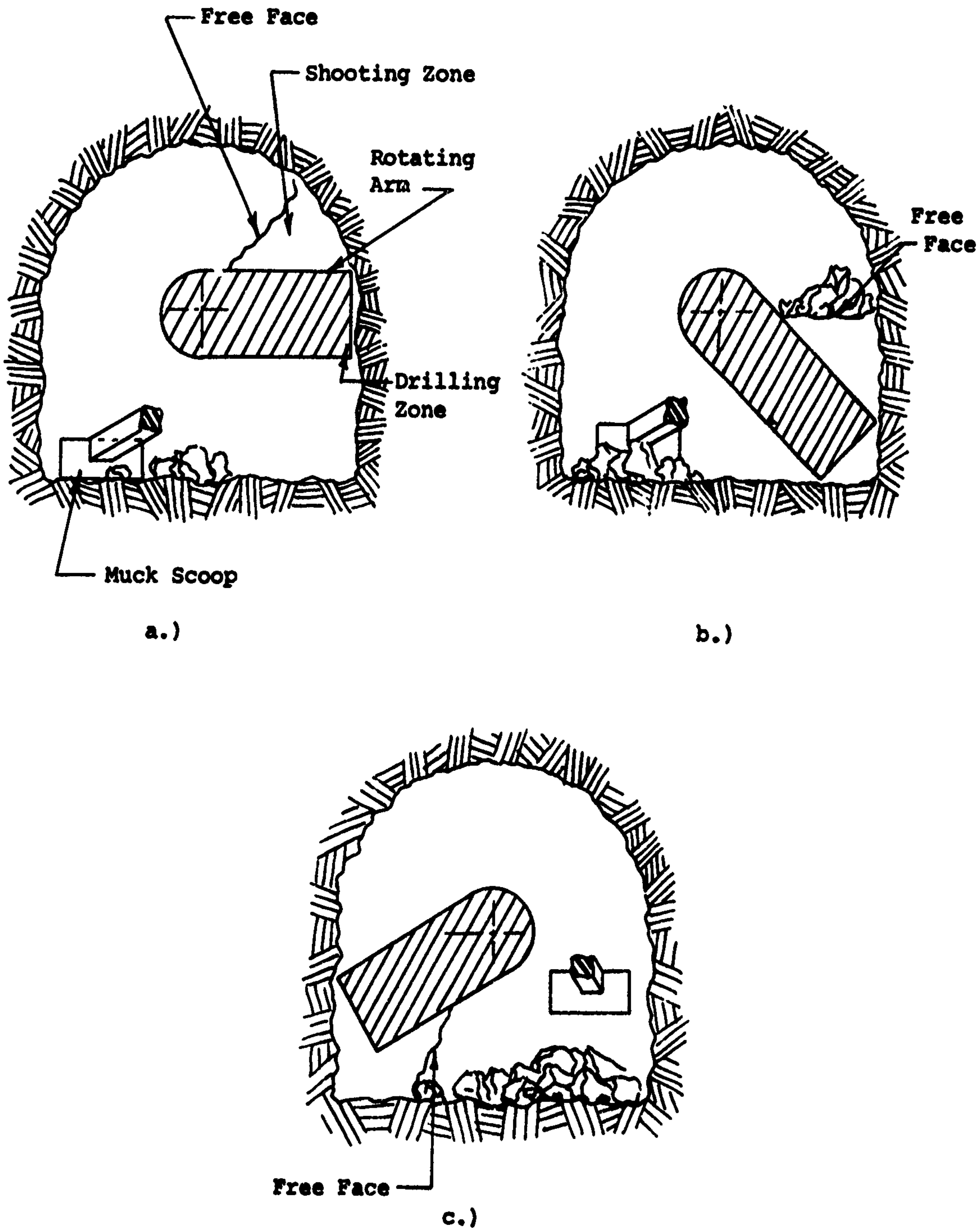


Figure 13

Mucking Sequence

Figure 13b. In this position most fragments will fly from the blast area to the floor on the left, but some will stay on the free face and some may also come to rest on top of the shield (for this reason, the shield will not be any wider than necessary.) The scoop is still working in the lower left quadrant to assure that it is clear as the rotating equipment moves into this quadrant.

Between Figures 13b and c the muck scoop is retracted to pass behind the rotating equipment with, perhaps, a short period without mucking. When the rotating equipment has moved sufficiently to the left, as in Figure 13c, the scoop is free to work on the accumulated material in the lower right quadrant. In this position, and until the free face moves up to the horizontal position, it will probably be necessary to retract the muck scoop out of the direct path of blast fragments during blasting, but work can continue in front of the vehicle near the apron.

If blasting can be adjusted to produce reasonably uniform and small fragments, a simple gathering system like that used on continuous coal miners could be made to work. To this end, the goals of the Physics International work (3) are valuable in the development of a continuous drill and blast machine. Also, more compact hydraulic drills which would permit drilling more nearly parallel to the floor, thereby reducing the amplitude of floor irregularities, would also be helpful.

One manufacturer even suggested that mucking could be accomplished by a vacuum system. This may not be directly applicable if large fragments are common, but with proper fragmentation behavior it may be possible.

5.6 Operator Protection

Many of the operations of the machine can be easily automated, and eventually perhaps all can be. For the present, however, it seems that some operations (notably mucking) should be under remote manual control. If the operator is on the machine, he must be enclosed in a protective cab as previously mentioned. However, operator protection may be more easily and safely provided by true remote control with closed circuit TV monitoring. Suitable cameras and techniques are available (even capable of seeing through smoke) and cameras would be more easily enclosed than a man. (7)

At least two monitoring cameras would be necessary: one to follow mucking activity, and a second to permit accurate positioning and insertion of the explosive loading equipment. This latter, mounted on the shield, would give better visibility than possible even from an on-the-scene protective cab. Of course, a camera in this position must be heavily shielded, including a cover that closes over the lens when the loading mechanism shifts to the initiation position (Figure 11 sequence).

5.7 The Model

A simple model has been constructed to better illustrate the unusual three-dimensional tunnel geometry. Photos of the spiral face geometry were seen in Figure 6.

The model is made up of a nesting set of pie shaped segments corresponding to those shown in the blast pattern of Figure 5. These are contained in a clear plastic "roof" element. The end of each segment is shaped to the spiral face form so that, when nested properly the complete idealized spiral geometry is formed, with the side of one segment forming the free face. Removal of one "pie shaped" blast segment is simulated by sliding the appropriate wooden segment ahead one spiral pitch, thereby exposing the side of the next segment. In this way the ideal spiral geometry can be illustrated for all positions of the free face.

A simple model of the continuous drill and blast machine was also constructed to show its operation relative to the face geometry. This model is shown in Figure 14, and again inside the "tunnel" in Figure 15. The radial arm may be rotated to match the machine to any desired position of the free face (but the arm length is not variable to reach the lower corners.)

6. Performance Projection

Average or continuous advance rate will depend upon the performance of individual components and the manner in which these components can be combined in the removal of each segment. At present, assuming the development of satisfactory automated injection and initiation equipment, an attractive overall performance can be projected around today's pneumatic drilling equipment. At present, such drills are easily capable of drilling speeds of 4 feet per minute in hard rock.

Under the worst conditions it will be necessary to drill, load, and shoot each "spoke" of blast holes before the next spoke is drilled in order to avoid blast damage to pre-drilled holes. Then

Figure 14

Continuous Spiral Drill and Blast

Tunneling Machine

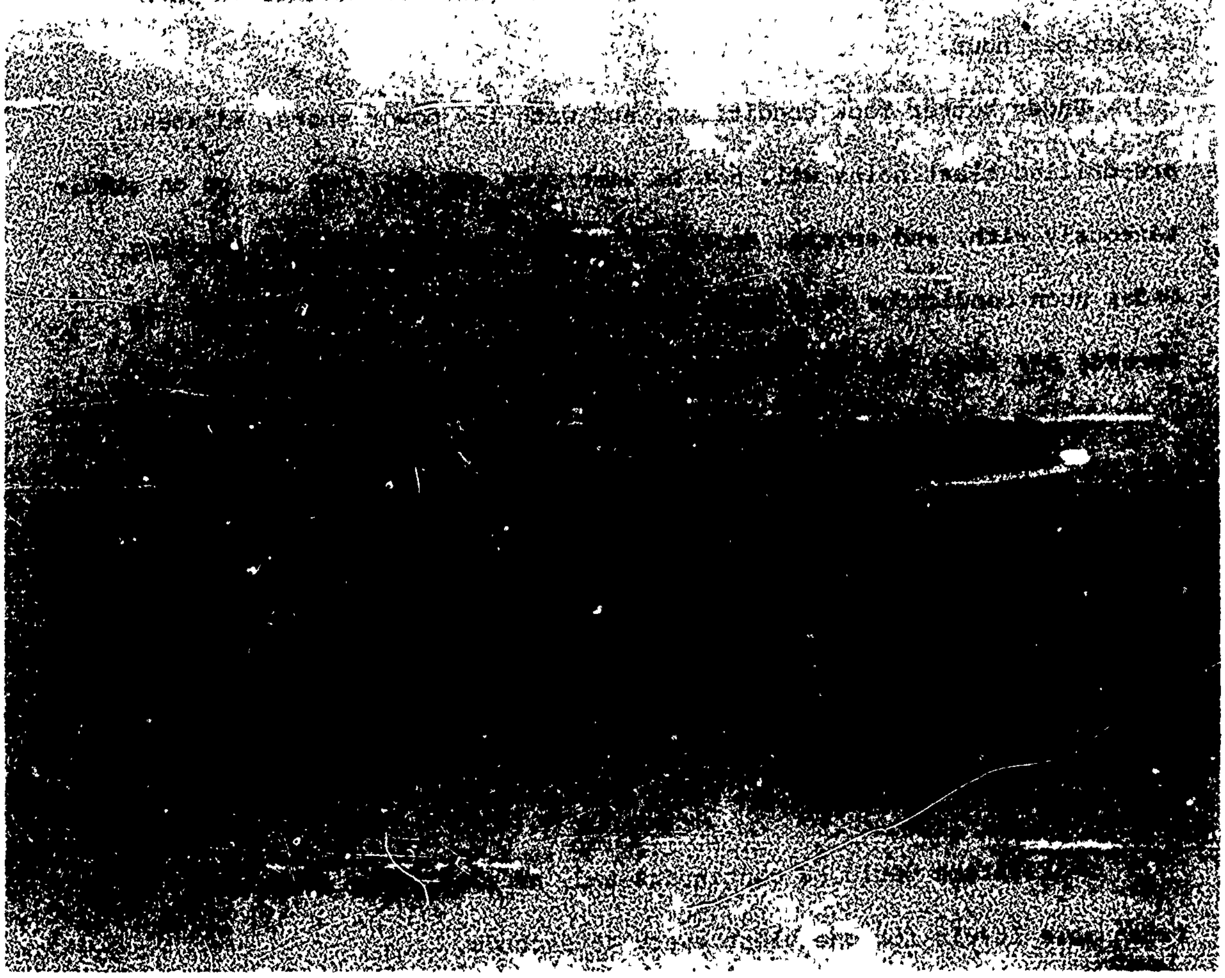


Figure 15

Tunneling Machine Inside

Model Tunnel

the following timing seems possible: drill three holes simultaneously 1 minute; move to inject explosive, 1/2 minute; inject explosive, 1/2 minute; shoot and move to next drill site, 1/2 minute. Thus, each spoke consumes 2 1/2 minutes. Since there are 12 spokes, one revolution or 4 feet of advance takes just 30 minutes. The rate of advance is then 8 feet per hour.

Under better rock conditions, and with low power shots, adjacent, pre-drilled blast holes will not be destroyed and drilling can go on simultaneously with, and several spokes in advance of, loading and shooting. Under such conditions each spoke can be completed in 1 1/2 minutes (45 seconds per shot) and the advance rate can be 13.3 feet per hour.

These represent advance rates without shut down of course, and it will be some time before a complete machine is developed to reliably proceed at these rates. On the other hand, note that the figures are based on 48 inches per minute drilling speed - well within today's capability in hard rock. In softer rock rates in excess of 60 inches per minute are not unusual, and within two years such rates will be common in hard rock.

Ventilation would be continuous and, as previously calculated, at reasonable levels for one blast every 45 seconds.

Mucking will also be virtually continuous at a modest level. Advance at 13.3 feet per hour corresponds to excavation at the rate of 12.6 cubic feet per minute in a heading of 57 square feet. With a 10 per cent overbreak and 50 per cent swell factor, the muck flow would be about 21 cubic feet per minute. With permissible conveyor speeds of the order of 200 to 300 feet per minute, this is a very small muck flow. The preliminary design includes a 36 inch conveyor to handle large pieces, not to handle a large flow. As in all aspects of the concept, exciting excavation rates are compatible with modest component performance if the individual components can only be permitted to operate continuously.

7. Conclusions and Recommendations

The RAPIDEX continuous drill and blast concept is based upon an unusual spiral blast pattern that permits frequent small blasts while maintaining high blasting efficiency. With small blasts a machine can be designed to remain at the face to perform drilling, loading, shooting, mucking, and ventilation functions in a virtually continuous manner.

It can be concluded that the blast pattern, per se, is feasible on the safe grounds that, in the course of this study, it was discovered that the pattern has been used successfully for shaft sinking. Furthermore, in cooperation with experienced blasting personnel, a reasonable, specific pattern has evolved for an 8 x 8 foot horseshoe heading.

Preliminary design work leads to the conclusion that conventional components (except for automated loading and initiation components) can be combined in a reasonable design of exciting overall performance capabilities.

Experimental work in a related program has identified explosive agents and an initiation scheme satisfactory for the necessary automation of loading and initiation. That work, however, has been terminated prior to the design and development of specific components for field work.

In general then, it can be concluded that the concept is entirely feasible. Considerable engineering work remains in the development of an operational tunneling tool for routine application, but no formidable obstacles are foreseen at this time.

At present it would seem that no further study or preliminary design work is justified without the gathering of specific information on the spiral blast geometry. It is recommended, therefor, that the program be continued with a series of field tests. It would be premature to recommend a full scale prototype development program at this time.

Fortunately, a development program can be broken into relatively simple steps to progressively solve the more unusual problems before undertaking the expense of full scale hardware procurement. The following series is recommended:

1. Develop satisfactory blasting performance in a full scale field test using conventional (i.e., hand held) equipment and conventional explosives. In addition to providing specific hole pattern and loading data, this program would yield quantitative data on shield design requirements.
2. Select specific explosive agents and initiation requirements from the satisfactory candidates already identified.

3. Duplicate the developments of step 1 (deliberately undertaken with conventional explosive) with the new explosive agents and field test the initiation requirements still using no automated equipment.

4. With the results of these field tests, design and test a shield, using dummy components as appropriate to avoid damage to expensive prototype components. Again, no automated equipment need be involved.

This series of tests would explore all unusual design requirements for the front end of a complete continuous drill and blast tunneling machine. If satisfactory performance is achieved, it would then be appropriate to go ahead with full scale development of the complete machine.

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